Spatiotemporal changes of typical glaciers and their responses to climate change in Xinjiang, Northwest China

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Abstract: Glaciers are highly sensitive to climate change and are undergoing significant changes in mid-latitudes. In this study, we analyzed the spatiotemporal changes of typical glaciers and their responses to climate change in the period of 1990–2015 in 4 different mountainous sub-regions in Xinjiang Uygur Autonomous Region of Northwest China: the Bogda Peak and Karlik Mountain sub-regions in the Tianshan Mountains; the Yinsugaiti Glacier sub-region in the Karakorum Mountains; and the Youyi Peak sub-region in the Altay Mountains. The standardized snow cover index (NDSI) and correlation analysis were used to reveal the glacier area changes in the 4 sub-regions from 1990 to 2015. Glacial areas in the Bogda Peak, Karlik Mountain, Yinsugaiti Glacier, and Youyi Peak sub-regions in the period of 1990–2015 decreased by 57.7, 369.1, 369.1, and 170.4 km², respectively. Analysis of glacier area center of gravity showed that quadrant changes of glacier areas in the 4 sub-regions moved towards the origin. Glacier area on the south aspect of the Karlik Mountain sub-region was larger than that on the north aspect, while glacier areas on the north aspect of the other 3 sub-regions were larger than those on the south aspect. Increased precipitation in the Karlik Mountain sub-region inhibited the retreat of glaciers to a certain extent. However, glacier area changes in the Bogda Peak and Youyi Peak sub-regions were not sensitive to the increased precipitation. On a seasonal time scale, glacier area changes in the Bogda Peak, Karlik Mountain, Yinsugaiti Glacier, and Youyi Peak sub-regions were mainly caused by accumulated temperature in the wet season; on an annual time scale, the correlation coefficient between glacier area and annual average temperature was –0.72 and passed the significance test at $P<0.05$ level in the Karlik Mountain sub-region. The findings of this study can provide a scientific basis for water resources management in the arid and semi-arid regions of Northwest China in the context of global warming.

Keywords: glacier area change; normalized snow cover index (NDSI); climate change; remote sensing; Altay Mountains; Tianshan Mountains; Karakorum Mountains

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1 Introduction

Glacier, as a water reservoir, plays an important role in the global water cycle (IPCC, 2013). It is not only the source of many rivers and lakes, but also the main source of water in arid and semi-arid regions. As a stable supply source of rivers, glaciers have a large influence on regulating annual runoff and hence regional ecological balance (Walter et al., 2010; Jacob et al., 2012; Sorg et al., 2012; Sun et al., 2015; Yang et al., 2014; Zhang et al., 2020; Chen et al., 2021). Studies of global glacier area changes over the last 40 a have demonstrated that different geographical locations have experienced different temperature and precipitation changes, and have undergone different glacier area changes (Kamb et al., 1985; Yao et al., 2012; Dehecq et al., 2019). From the global perspective, glacier area change and climate change have a close relationship (Cook et al., 2005; Kang et al., 2010; Scherler et al., 2011; Jacob et al., 2012; Yang et al., 2014; Sun et al., 2015; Gao et al., 2018; Quirk et al., 2020).

The size of a glacier determines its sensitivity to climate change and its response time to the key meteorological factors. According to Ding (1995), glaciers longer than 5 km in length have an 8-a response time, while glaciers shorter than 5 km have a 2-a response time. Wang (1992) showed that mountain glaciers in the Northern Hemisphere will take 12–13 a to respond to climate change. The mountain glacier area in the Northern Hemisphere will retreat as a result of global warming (Kang et al., 2010). Zhang et al. (2010) found that glaciers with small areas in the low latitudes of the Northern Hemisphere were more sensitive to climate change.

The Xinjiang Uygur Autonomous Region of Northwest China has the largest number of mountain glaciers in the middle and low latitude regions of the world (Shi, 1988). In Xinjiang, there are about 19,374 glaciers covering an area of 0.26×10^{6} km^{2} and a total ice reserve of 0.27×10^{12} m^{3}. These glaciers are unevenly distributed and mainly concentrated in the western half of the region. Ice storage capacity is about 29 times that of surface runoff, providing 0.20×10^{12} m^{3} of meltwater every year, which is the main water source for oasis irrigation in Xinjiang (Huang, 1984). Mountain glacier meltwater is also an important part of the water resources cycle in Xinjiang. For example, glaciers in the Karakorum Mountains are the sources of the Hotan River and the Yarkant River.

The accumulation and melting of glaciers are of great significance to the sustainable development of Xinjiang and even the entire northwestern region of China (Zhou, 2013). The continuous retreat of mountain glaciers in the middle and low latitudes is the most powerful and direct evidence of global climate warming (Liu et al., 2005). The intensity of glacier accumulation and melting is mainly affected by precipitation and temperature, in which temperature determines melting and precipitation determines accumulation (Tian et al., 2012). Therefore, it is important to understand the variations of the driving forces that affect glaciers in Xinjiang.

The Altay Mountains in the north, the Karakorum Mountains in the south, and the Tianshan Mountains in the center constitute the 3 major mountain ranges in Xinjiang. The Bogda Peak sub-region is the largest area of glaciers in the eastern Tianshan Mountains, and glaciers in the Karlik Mountain sub-region in the eastern part of the Tianshan Mountains are relatively developed and have been extensively studied (Qian et al., 2011; Sorg et al., 2012; Niu et al., 2014; Li et al., 2016). The Yinsugaiti Glacier is a typical large moraine-covered glacier and is located in the Karakorum Mountains. The Youyi Peak sub-region is located in the northern part of the Altay Mountains and is the highest latitude modern glacier distribution area in China (Bai et al., 2012).

In this study, we used Landsat data with high spatial resolution and long-time series to analyze glacier area changes in 4 different mountainous sub-regions from 1990 to 2015. By comparing glacier area changes in the selected 4 typical sub-regions, the change trends of glaciers were explained. Further, a correlation analysis method was used to analyze changes in temperature and precipitation from 1960 to 2014, with the aim of providing a scientific foundation for water

resources management in Xinjiang in the face of global warming.

2 Materials and methods

2.1 Study sites

Xinjiang Uygur Autonomous Region in Northwest China is situated in the arid region of Central Asia. Xinjiang has a continental climate characterized by long periods of sunshine duration, low precipitation, high-speed winds often carrying sand, and large daily and annual ranges of temperature in the low altitudes (Wang et al., 2020). In this study, 4 sub-regions in the 3 major mountain ranges in Xinjiang were selected: the Bogda Peak, Karlik Mountain, Yinsugaiti Glacier, and Youyi Peak sub-regions (Fig. 1).

The Bogda Peak is the main peak of the Bogda Mountains, located in the eastern Tianshan Mountains. It is located between 87°50′–88°30′E and 43°33′–43°54′N. The high and steep terrain provides good spatial conditions for glacier development. Modern glaciers distributed in the Bogda Peak sub-region are the sources of many rivers (Niu et al., 2014). According to Niu et al. (2014), the average scale of glaciers in the Bogda Peak sub-region was 0.78 km^2 in 2001. In this sub-region, there are many small glaciers, which are sensitive to climate change (Qian et al., 2011).

The Karlik Mountain is located between 93°41′–95°07′E and 42°50′–43°35′N. It is the easternmost section of the Tianshan Mountains. The sub-region has an area of 100.54 km^2 (Hu et al., 1979) and is characterized by a dry continental climate influenced by the westerly winds (Hu et al., 1979). Glaciers are developed in the Karlik Mountain sub-region.

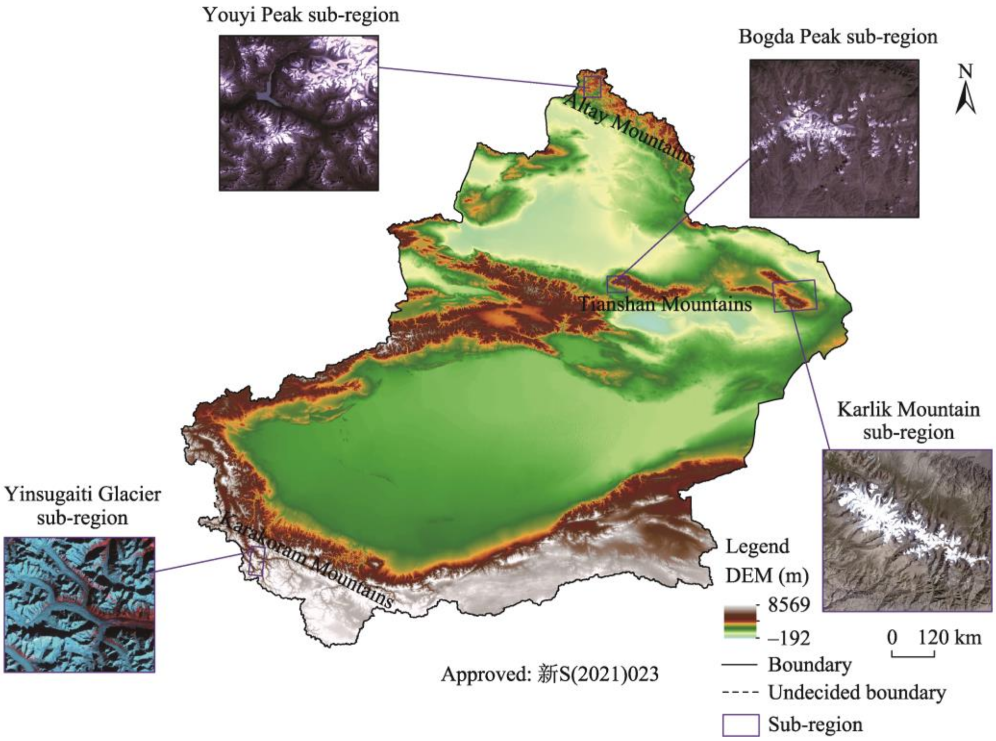

Fig. 1 Overview of major mountain ranges in Xinjiang and Landsat images of the selected 4 sub-regions (the Bogda Peak sub-region, the Karlik Mountain sub-region, the Yinsugaiti Glacier sub-region, and the Youyi Peak sub-region). The Landsat images were downloaded from the United States Geological Survey (USGS) (http://www. glovis.usgs.gov). Note that the Digital Elevation Model (DEM) map is based on the standard map (新 S(2021)023) of the Map Service System (https://xinjiang.tianditu.gov.cn/main/bzdt.html) marked by the Xinjiang Uygur Autonomous Region Platform for Common Geospatial Information Services, and the standard map has not been modified.

The Yinsugaiti Glacier sub-region lies between 75°55′–76°21′E and 35°55′–36°15′N. Due to recharge from accumulation areas in the north, west, and south, a massive valley glacier was developed, with branches formed by the confluence of 4 rivers.

The Youyi Peak sub-region is on the northern side of the central Altay Mountains and is located between 87°00′–88°00′E and 48°40′–49°10′N. It is the highest latitude region where modern glaciers are distributed in China.

2.2 Data sources

2.2.1 Remote sensing data and Digital Elevation Model (DEM)

Landsat TM and ETM+ images were downloaded from the United States Geological Survey (USGS) (http://www.glovis.usgs.gov). The downloaded remote sensing data had passed the system radiometric correction and ground control point geometric correction, and were processed by DEM correction. To facilitate the analysis, we unified the coordinate system of the remote sensing data (remote sensing images, DEM, and glacier catalog data) in each period. The spatial resolution of Landsat TM and ETM+ images was 30 m. To reduce the error caused by glacier changes over time as well as to minimize the influence of snow on the extraction of glacier boundaries, we selected the smallest image boundary of the glacier boundary in July–September for every 3 a in the period of 1990–2015 as the base map. All image details are summarized in Table 1.

Gaofen-1 images were also used in this study. Gaofen-1 was the first low-earth-orbit remote sensing satellite with a design life of more than 5 a in China (http://www.cresda.com). It adopted CAST2000small satellite platform technology and carried 6 high-resolution cameras as well as multispectral wide-range cameras (China Great Wall Industry Corporation, Beijing, China) with different bands and resolutions. The satellite has an orbital altitude of 645 km, and the visibility range of the high-resolution camera with a 25° sideway was 700 km, allowing for a 4-d revisit. When the side swing function was not used, the coverage days were 41 d. For the wide-angle camera, the satellite could achieve 4 d of global coverage without pendulum measurement.

The DEM data were mainly used for extracting glacier boundary data and performing glacier change analysis. The data were downloaded from the China International Scientific Data Service Platform (http://datamirror.csdb.cn/index.jsp). Further, ASTER Global Digital Elevation Model (GDEM) with a spatial resolution of 30 m×30 m and Shuttle Radar Topography Mission (STRM) 4.1 product with a spatial resolution of 90 m×90 m were selected.

2.2.2 Meteorological data

Precipitation, temperature, and their combination are the critical climatic factors affecting the development of glaciers. Precipitation determines glacier accumulation and temperature affects glacier melting (Duan et al., 2009). Their combined influence determines the nature, development, and evolution of glaciers (Bai et al., 2012; Zhang et al., 2012; Zhu et al., 2014). Since meteorological stations are all located far from the sub-regions, it was challenging to find relevant meteorological data. Hence, gridded monthly temperature and precipitation data were used in this study. The grid point dataset (v2.0), with a resolution of 0.5°×0.5° and covering the period from 1961 to 2014, was downloaded from the China Meteorological Data Service Centre (http://data.cma.cn/en). These data accurately describe the spatial characteristics of precipitation near the mountainous terrain in Xinjiang (Zhao et al., 2014; Zhao and Zhu, 2015) and can be used to explore the relationship between glacier area change and climate change. Temperature and precipitation values were calculated by using the average of the grid data in the 4 sub-regions.

2.2.3 Other data

The National Cryosphere Desert Data Center (http://www.ncdc.ac.cn/portal/) provides the first and second glacier inventory datasets of China (v1.0). These glacier inventory data were mainly used to extract glacier boundaries of the 4 sub-regions.

2.3 Data analysis

2.3.1 Normalized snow cover index (NDSI)

The NDSI method, which can detect strong reflectivity in the red band of visible light and strong

Table 1 Details of the Landsat images (from 1990 to 2015) used in this study

Sub-region	Strip number	Imaging date	Sensor	Cloud (%)	Resolution (m)	NDSI extraction threshold
Bogda Peak	142/30	26 Jul 1992	TM	6	30	0.00–0.95
	142/30	16 Jul 1994	TM	0	30	0.00–0.95
	142/30	13 Sep 1998	TM	8	30	0.10–0.92
	142/30	2 Sep 2000	TM	1	30	0.10–1.00
	142/30	5 Sep 2004	ETM+	1	30	0.10–0.97
	142/30	29 Aug2007	ETM+	1	30	0.05–0.89
	142/30	13 Aug 2010	TM	0	30	0.10–1.00
	142/30	13 Aug 2012	ETM+	0	30	0.10–0.98
	142/30	1 Sep 2014	TM	13	30	0.10–1.00
Karlik Mountain	138/30	2 Sep 1992	TM	0	30	0.00–0.93
	138/30	21 Aug 1994	TM	0	30	0.00–1.00
	138/30	10 Aug 1996	TM	0	30	0.00–0.95
	138/30	2 Sep 2000	TM	1	30	0.00–0.94
	138/30	24 Aug 2001	TM	16	30	0.00–0.98
	138/30	28 Sep 2002	TM	1	30	0.00–0.99
	138/30	22 Aug 2006	TM	0	30	0.00–0.93
	138/30	11 Aug 2008	TM	0	30	0.00–0.95
	138/30	4 Aug 2014	O LI	0	30	0.00–0.92
Yinsugaiti Glacier	148/35	24 Oct 1992	TM	25	30	0.10–0.92
	148/35	26 Jul 1994	TM	14	30	0.20–1.00
	148/35	20 Sep 1997	TM	2	30	0.10–0.94
	148/35	2 Sep 2000	TM	1	30	0.00–0.94
	148/35	21 Jul 2001	ETM+	6	30	0.35–0.92
	148/35	14 Aug 2004	ETM+	1	30	0.10–0.94
	148/35	27 Nov 2007	ETM+	6	30	0.10–0.94
	148/35	23 Aug 2010	TM	0	30	0.10–0.94
	148/35	10 Oct 2013	ETM+	2	30	0.30–1.00
	148/35	25 Jul 2014	ETM+	4	30	0.20–1.00
Youyi Peak	144/26	25 Aug 1989	TM	10	30	0.30–0.94
	144/26	28 Aug 1993	TM	0	30	0.20–0.96
	144/26	26 Aug 1998	TM	5	30	0.00–0.95
	144/26	7 Aug 2000	ETM+	7	30	0.20–0.93
	144/26	18 Aug 2004	ETM+	15	30	0.40–1.00
	144/26	12 Sep 2007	ETM+	0	30	0.40–1.00
	144/26	13 Aug 2008	ETM+	17	30	0.50–1.00
	144/26	7 Sep 2011	ETM+	0	30	0.20–0.94
	144/26	10 Sep 2015	OLI	1	30	0.00–0.92

Note: NDSI, normalized snow cover index.

absorption characteristics in the short-wave infrared radiation band, was used to distinguish ice and snow from surrounding ground. The specific equation used is as follows:

$$\mathrm{NDSI}=\frac{CH_n-CH_m}{CH_n+CH_m}, \tag{1}$$

where CH_n and CH_m are the visible band number and near-infrared band number, respectively. The grayscale value of NDSI ranges from –1 to 1. An appropriate threshold can be set to obtain more accurate results.

2.3.2 Glacier boundary extraction and verification

Sensor error and image alignment error are the main error sources that affect the accuracy of glacier boundary extraction. This paper selected the smallest glacier boundary to estimate the glacier area every 3 a and this area was used to analyze glacier area change.

For the first verification method of the boundary extraction, we compared the Landsat image of 1 September, 2014 with the high-resolution Gaofen-1 image of 6 September, 2014 for glacier areas of the Bogda Peak sub-region (Fig. 2). Glacier boundaries on Gaofen-1 image were extracted using a visual interpretation method. Using ArcGIS platform, we randomly generated 50 points along the glacier boundaries decoded on Landsat image, and then these points were superimposed on Gaofen-1 image with their visually defined boundaries. The error between the two images was found to be about 2.0%.

The second verification method was the ratio of the calculated glacier area from Gaofen-1 satellite image to the extracted glacier area from Landsat image (Guo et al., 2013). For this method, the error was found to be about 0.6%.

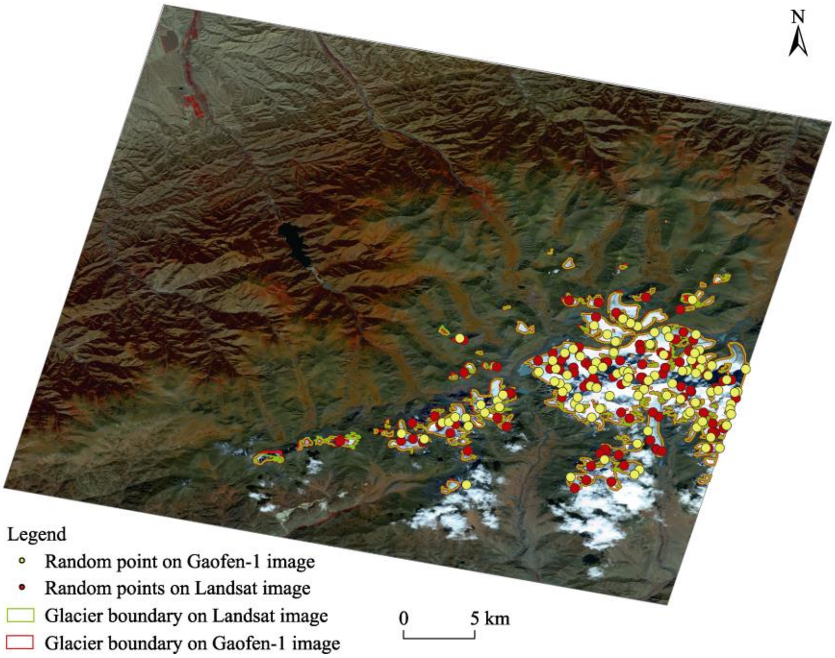

Fig. 2 Comparison of the calculated glacier area from Gaofen-1 satellite image and the extracted glacier area from Landsat image in the Bogda Peak sub-region in 2014

2.3.3 Glacier area change rate

The glacier area change rate is a common index used to evaluate the degree of glacier area change.

This index can unify and compare the results of glacier area change at different time scales. The index was calculated as follows (He et al., 2015):

$$A_{APAC} = \frac{\Delta s}{\Delta t \times s_0} \times 100\% , \tag{2}$$

where A_{APAC} is the glacier area change rate (%/a); Δs is the glacier area change (km^2); Δt represents the time interval of the study period (a); and s_0 represents the initial glacier area (km^2).

2.3.4 Extraction of glacier attributes

Three glacier attributes were used to further document glacier changes, i.e., glacier area, glacier aspect, and the glacier area center of gravity. Glacier structure is an important factor in glacier research. Different glacier types have different responses to meteorological factors. Moreover, the study of the change in the glacier area center of gravity has a certain predictive value for future glacier morphological changes. The glacier area center of gravity means the geometric center of glacier area in each sub-region and it can be derived from ArcGIS. Each of the 4 sub-regions were divided into 4 quadrants by taking the glacier area center in the sub-region during the period 1990–1992. A horizontal axis was then defined east and west from the center, while a vertical axis was defined north and south from the center. We defined the northeast quadrant as the first quadrant, the northwest as the second, the southwest as the third, and the southeast as the fourth. The size of the abscissa represented the change of its area relative to the area in the quadrant from 1990 to 1992, and the angle with the x axis represented the direction of its change with the glacier area center of gravity. This analysis aimed to explore the changes of the glacier area center of gravity in the different sub-regions.

Glacier aspect is another principal factor affecting glacier area change (Wang et al., 2013). Due to the influence of topography, solar radiation, and other factors, glacier area change in different ways was depended on the aspect direction. The aspect direction of each glacier area was analyzed using DEM data and ArcGIS. Glacier areas of the 4 sub-regions were classified into 8 aspect directions: north, south, west, east, northeast, southeast, southeast, and northwest. Then, glacier areas of the different aspect directions in each sub-region were calculated.

3 Results

3.1 Changes of glacier area

Glacier boundaries of the 4 sub-regions in different periods are presented in Figure 3. Glacier areas in the 4 sub-regions showed varying decreasing trends throughout the study period. Glacier areas in the Bogda Peak, Karlik Mountain, Yinsugaiti Glacier, and Youyi Peak sub-regions in the period of 1990–2015 decreased by 57.7, 369.1, 369.1, and 170.4 km^2, respectively. It should be noted that they showed increasing trends from 2002 to 2004 (Fig. 4). In the Bogda Peak sub-region, the periods of the maximum and minimum glacier area retreat rates were 1996–1998 and 2002–2004, respectively. The whole glacier area retreat rate was 4.58% during 2005–2015. In the Karlik Mountain sub-region, the periods of the maximum and minimum glacier area retreat rates were 2005–2007 and 2011–2013, respectively. The whole glacier area retreat rate was 17.78% during 2005–2015. In the Yinsugaiti Glacier sub-region, the periods of the maximum and minimum glacier area retreat rates were 1993–1995 and 2002–2004, respectively. From 2005 to 2015, the glacier area retreat rate of the total area was 2.20%. In the Youyi Peak sub-region, the periods of the maximum and minimum glacier area retreat rates were 1996–1998 and 2002–2004, respectively. From 2005 to 2015, the glacier area retreat rate of the whole sub-region was 13.79%. During 2005–2015, the glacier area retreat rate in all 4 sub-regions was slowed.

In general, glacier areas in the 4 sub-regions showed large-scale retreat trends in the 1990s, and then exhibited different downtrends and followed by an expansion trend from 2002 to 2004. During 2005–2015, the glacier area retreat rate in the 4 sub-regions showed decreasing trends. Compared to the average annual glacier area retreat rate of the 4 sub-regions, the retreat rate of the Youyi Peak sub-region was the highest, followed by the Bogda Peak sub-region, the Yinsugaiti Glacier sub-region, and the Karlik Mountain sub-region.

3.2 Changes of the glacier area center of gravity

The glacier area center of gravity in the 4 sub-regions showed a tendency to approach the origin in each sub-region (Fig. 5), indicating a retreat of glacier area in these 4 sub-regions from 1992 to

2015. Changes in the glacier area center of gravity in each quadrant of the 4 sub-regions from 1990 to 1995 were basically larger than those after 2005. This corresponded to the significant fluctuation of glacier area after 1990. Except for the Youyi Peak sub-region, glacier areas in the Bogda Peak, Karlik Mountain, and Yinsugaiti Glacier sub-regions exhibited obvious changes in the glacier area center of gravity in all 4 quadrants. The Youyi Peak sub-region only showed obvious changes of the glacier area center of gravity in the second and third quadrants, as well as noticeable changes in the east-west horizontal direction in the second quadrant (Fig. 5).

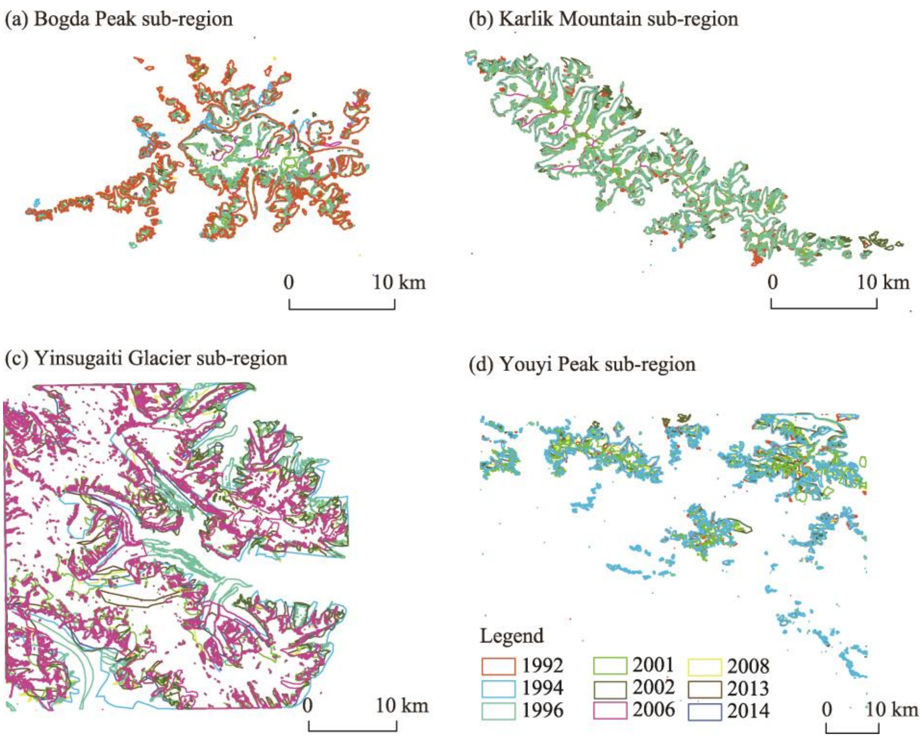

Fig. 3 Extracted glacier boundary results for the 4 sub-regions from 1992 to 2015. (a), Bogda Peak sub-region; (b), Karlik Mountain sub-region; (c), Yinsugaiti Glacier sub-region; (d), Youyi Peak sub-region.

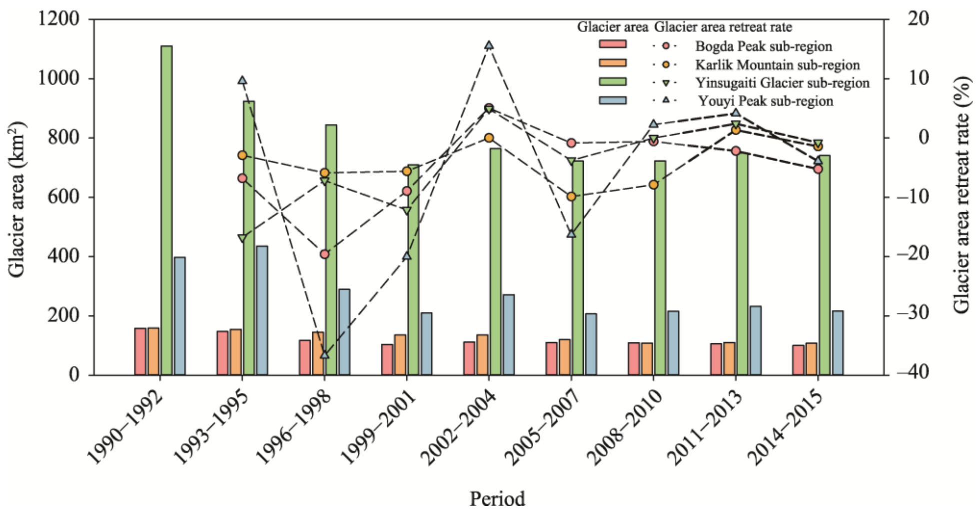

Fig. 4 Glacier area and its retreat rate in the 4 sub-regions from 1992 to 2015. The bar chart presents the glacier area and line graph presents the glacier area retreat rate.

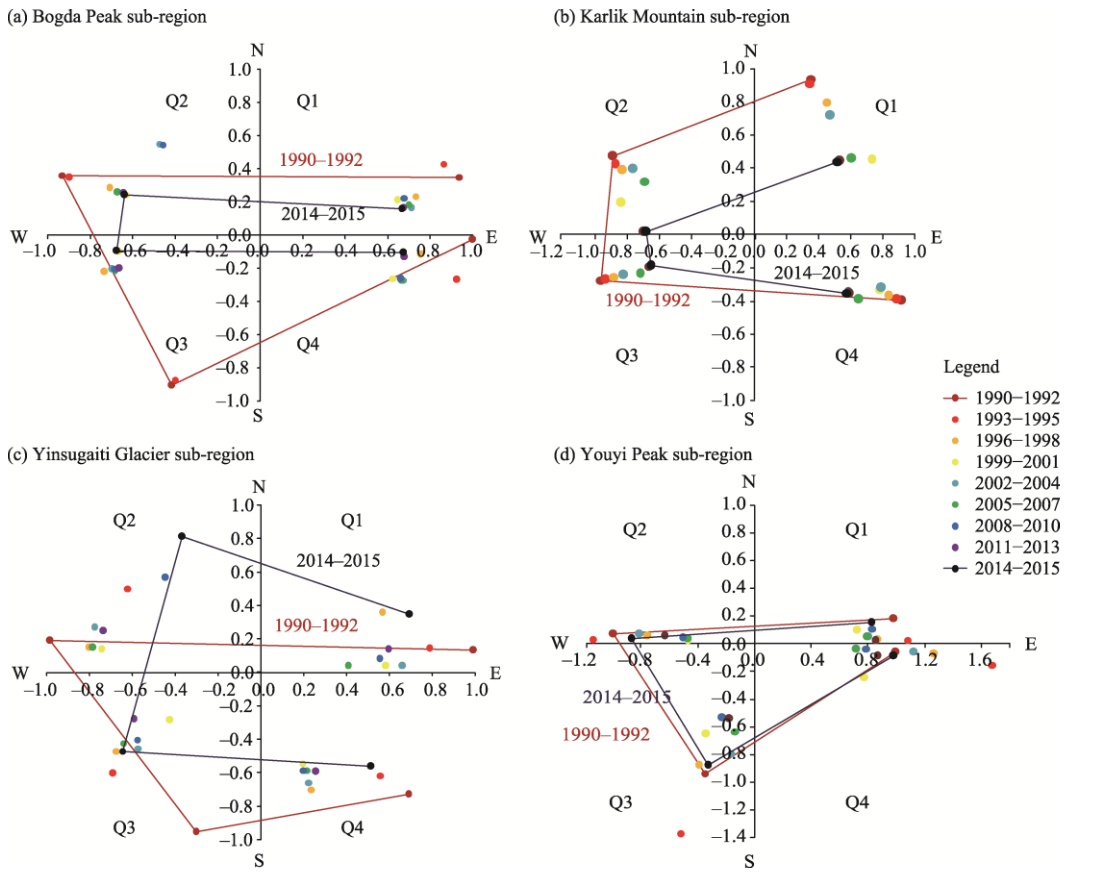

Fig. 5 Changes of the glacier area center of gravity in the 4 sub-regions from 1992 to 2015. (a), Bogda Peak sub-region; (b), Karlik Mountain sub-region; (c), Yinsugaiti Glacier sub-region; (d), Youyi Peak sub-region. Q1 represents the first quadrant, i.e., east to north; Q2 represents the second quadrant, i.e., north to west; Q3 represents the third quadrant, i.e., west to south; Q4 represents the fourth quadrant, i.e., south to east.

3.3 Changes of glacier aspect

Glacier areas in the Bogda Peak, Karlik Mountain, and Youyi Peak sub-regions are unevenly distributed (Wang et al., 2013). In this study, glacier areas lying on the east aspect were significantly greater than those on the other aspect directions (Fig. 6). Glaciers were more uniformly distributed in the Yinsugaiti Glacier sub-region than in the other 3 sub-regions, and there were more glaciers on each aspect direction. In contrast to the Karlik Mountain sub-region, glacier areas on the north aspect of the Bogda Peak, Yinsugaiti Glacier, and Youyi Peak sub-regions were greater than those on the south aspect of these sub-regions (Fig. 6).

In the Bogda Peak sub-region, the fast glacier area retreat rate was found on the southwest aspect (52.66%), followed by the northwest aspect (44.40%), and the lowest glacier area retreat rate was on the east aspect, with the value of 22.62%. In the Karlik Mountain sub-region, the fastest retreat rate was on the northwest aspect (44.40%), followed by the north aspect with a rate of 42.40%, and the smallest retreat rate was 19.50% on the east aspect. These variations were consistent with the retreat rates of glaciers in the eastern, middle and western parts of the Tianshan Mountains. In general, in the Tianshan Mountains, the glacier area retreat rate was the fastest in the western part, the second fastest in the middle part, and the slowest in the eastern part. Moreover, the northern part shrunk faster than the southern part and these characteristics were consistent with previous studies (Li et al., 2016; Yang et al., 2019). In the Yinsugaiti Glacier sub-region, glacier area on the east aspect shrunk the most, reaching 58.16%, followed by the south aspect (39.11%) and the north aspect (26.62%). The east aspect of the Youyi Peak

sub-region experienced the fastest glacier area retreat rate (22.37%), followed by the southeast aspect (20.64%) and the north aspect (0.33%).

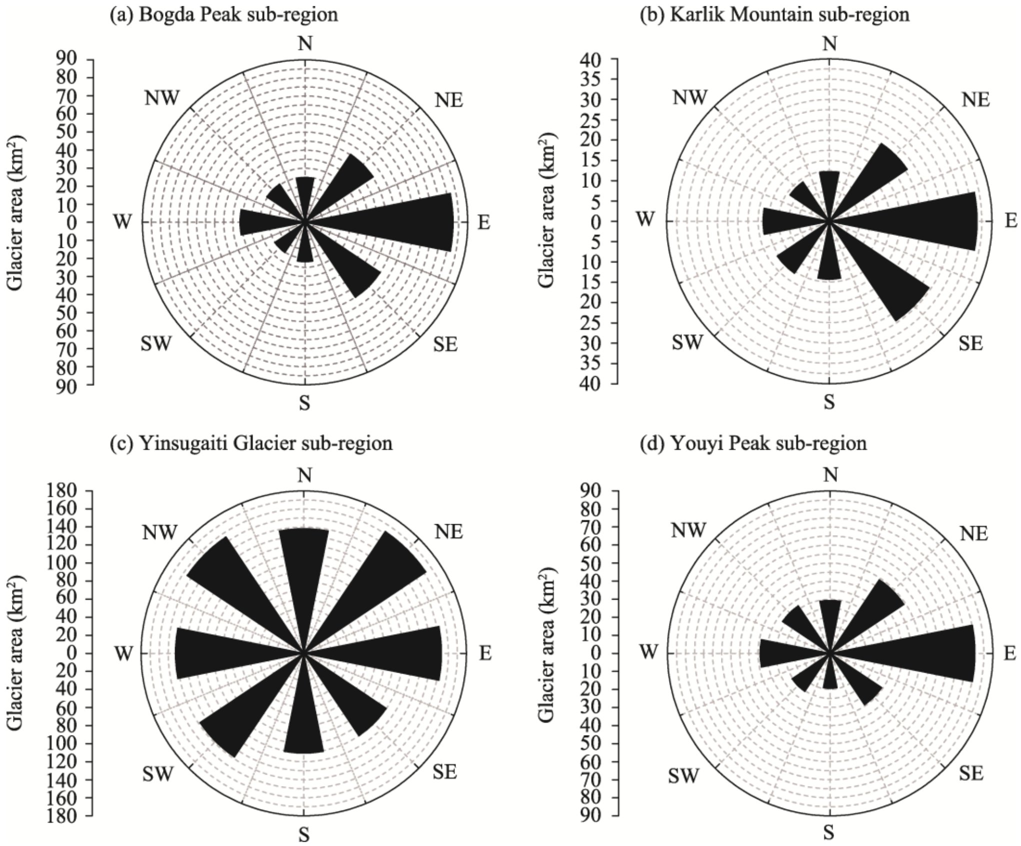

Fig. 6 Glacier area distribution on the different aspect directions in the 4 sub-regions in 1992. (a), Bogda Peak sub-region; (b), Karlik Mountain sub-region; (c), Yinsugaiti Glacier sub-region; (d), Youyi Peak sub-region. N, north; NE, northeast; E, east; SE, southeast; S, south; SW, southwest; W, west; NW, northwest.

Generally, current glaciers in the Bogda Peak, Karlik Mountain, and Yinsugaiti Glacier sub-regions all showed a retreat trend on each aspect direction. However, in the Youyi Peak sub-region, the glacier area retreat rate showed an increasing trend on the northwest aspect direction, and exhibited a retreating trend on the other aspect directions. In the Bogda Peak and Karlik Mountain sub-regions, the glacier area retreat rate was fastest on the northwest aspect and slowest on the east aspect. In the Yinsugaiti Glacier and Youyi Peak sub-regions, the glacier area retreat rate was fastest on the east aspect and slowest on the north aspect (Fig. 7).

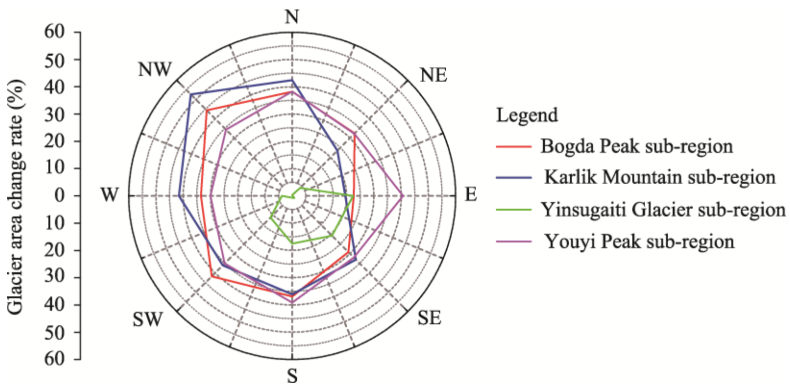

Fig. 7 Glacier area change rate on the different aspects in the 4 sub-regions in the period of 1992–2015

4 Discussion

4.1 Inter-annual changes of precipitation and temperature

From 1961 to 2014, annual precipitation of the 4 sub-regions showed an increasing trend. Specifically, annual precipitation of the Karlik Mountain sub-region clearly increased (0.05 significance level). The linear trend analysis showed that from 1961 to 2014, annual precipitation values of the Bogda Peak, Karlik Mountain, Yinsugaiti Glacier, and Youyi Peak sub-regions were 610.0, 212.3, 109.1, and 526.7 mm, respectively, and their precipitation increasing rates were 14.6, 9.1, 2.6, and 15.4 mm/10a, respectively (Figs. 8–11).

From 1961 to 2014, annual average temperature of the 4 sub-regions showed warming trends, with the Bogda Peak and Karlik Mountain sub-regions exhibiting significant increasing trends (P<0.05). The linear trend analysis showed that from 1961 to 2014, annual average temperature

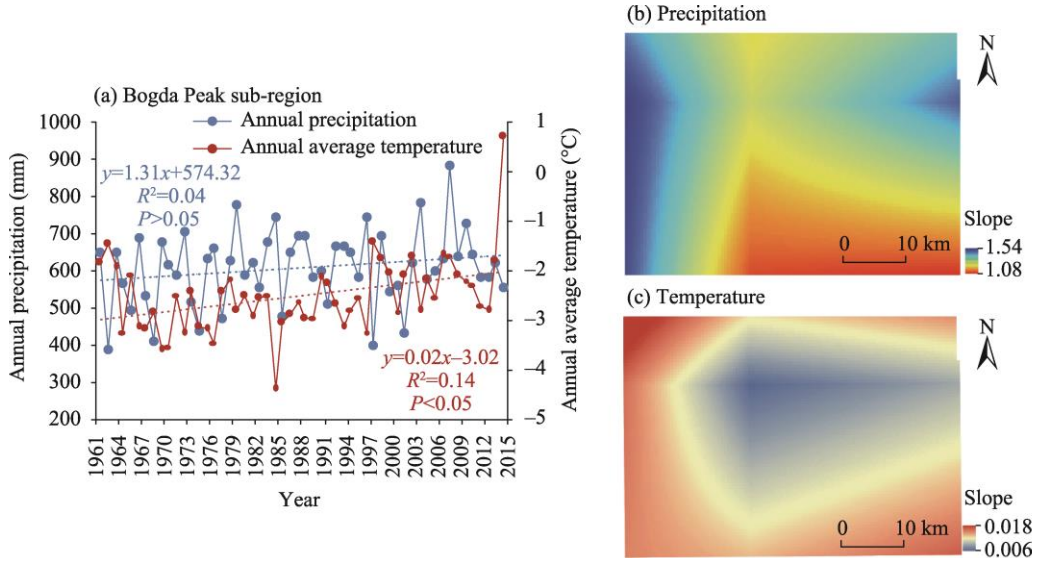

Fig. 8 Temporal changes of annual precipitation and annual average temperature (a) and spatial distributions of slopes of precipitation (b) and temperature (c) changes in the Bogda Peak sub-region from 1961 to 2014

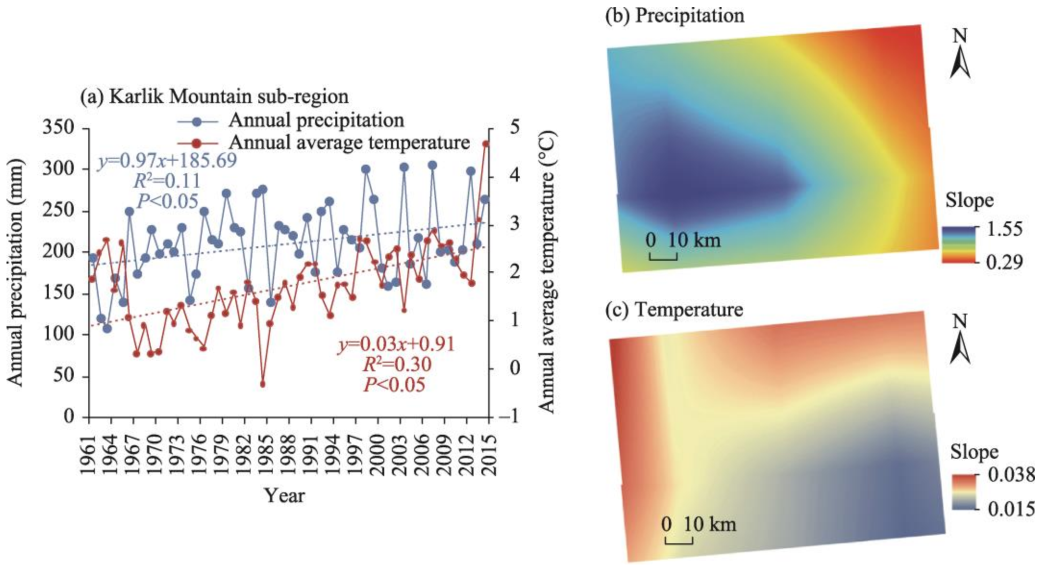

Fig. 9 Temporal changes of annual precipitation and annual average temperature (a) and spatial distributions of slopes of precipitation (b) and temperature (c) changes in the Karlik Mountain sub-region from 1961 to 2014

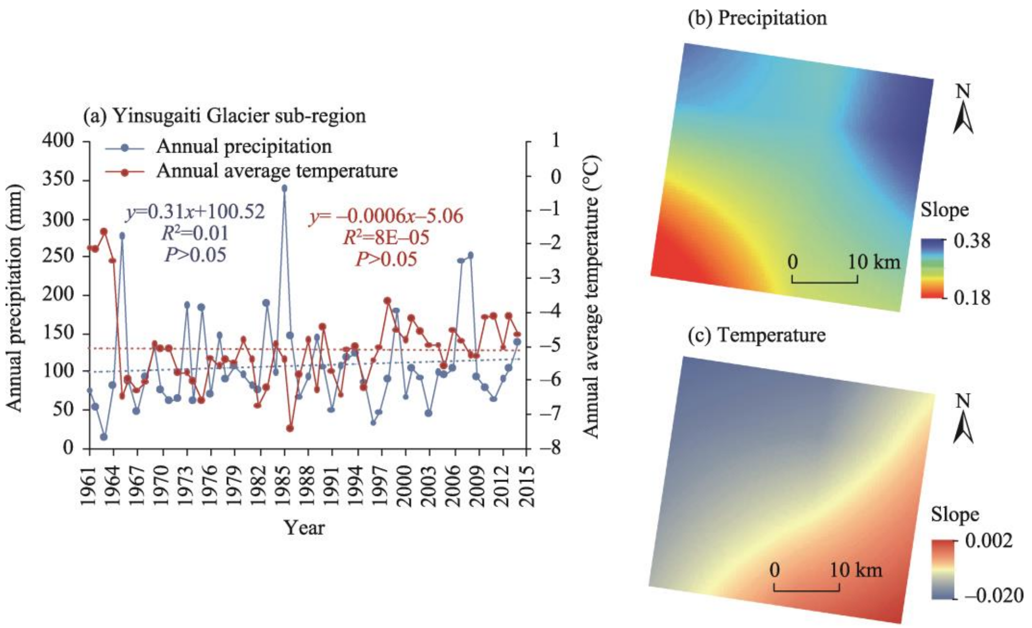

Fig. 10 Temporal changes of annual precipitation and annual average temperature (a) and spatial distributions of slopes of precipitation (b) and temperature (c) changes in the Yinsugaiti Glacier sub-region from 1961 to 2014

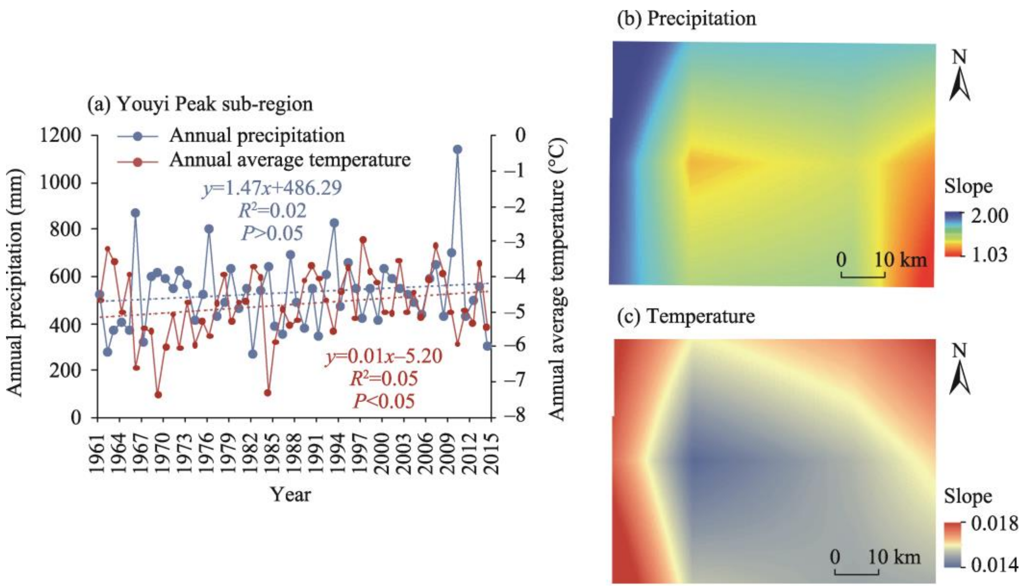

Fig. 11 Temporal changes of annual precipitation and annual average temperature (a) and spatial distributions of slopes of precipitation (b) and temperature (c) changes in Youyi Peak sub-region from 1961 to 2014

values of the Bogda Peak, Karlik Mountain, Yinsugaiti Glacier (after excluding the abnormal values), and Youyi Peak sub-regions were –2.5 ℃, 1.7 ℃, 5.1 ℃, and –4.8 ℃, respectively, with increasing rates of 0.2 ℃/10a, 0.3 ℃/10a, 0.3 ℃/10a, and 0.2 ℃/10a, respectively (Figs. 8–11).

From the above information, it can be concluded that the 4 sub-regions with the highest increasing rate of temperature, in descending order, were the Karlik Mountain, Yinsugaiti Glacier, Bogda Peak, and Youyi Peak sub-regions. The sub-regions with the highest increasing rate of precipitation in descending order were Youyi Peak, Bogda Peak, Karlik Mountain, and Yinsugaiti Glacier sub-regions. The Youyi Peak sub-region had the fastest glacier area retreat rate, followed by the Bogda Peak sub-region, the Yinsugaiti Glacier sub-region, and finally the Karlik Mountain

sub-region. It can be deduced that the response of the Youyi Peak sub-region to the key meteorological factors was found to be greater than those of the Bogda Peak, Yinsugaiti Glacier, and Karlik Mountain sub-regions. Moreover, the increase of precipitation in the Youyi Peak and Bogda Peak sub-regions had little effects on the glacier area retreat, while the increase of precipitation in the Karlik Mountain sub-region had a certain inhibitory effect on the glacier area retreat.

From the spatial distribution of the change rates of precipitation and temperature, it can be concluded that the areas with higher increasing rates of precipitation and temperature were mainly distributed along the edges of the 4 sub-regions (Figs. 8–11).

To better understand the rapid change of glacier areas in the 1990s, we calculated the mean values of temperature and precipitation for a 10-a time interval (Fig. 12). The results revealed that temperature in the Bogda Peak, Karlik Mountain, Yinsugaiti Glacier, and Youyi Peak sub-regions increased significantly in the 1990s, while precipitation decreased significantly in the Bogda Peak and Yinsugaiti Glacier sub-regions, and increased slightly in the Karlik Mountain sub-region. Glaciers of the Youyi Peak sub-region were sensitive to temperature, and the increase of precipitation could not compensate for the ablation of glaciers caused by temperature rise, which could explain the rapid change of glacier areas in the 1990s.

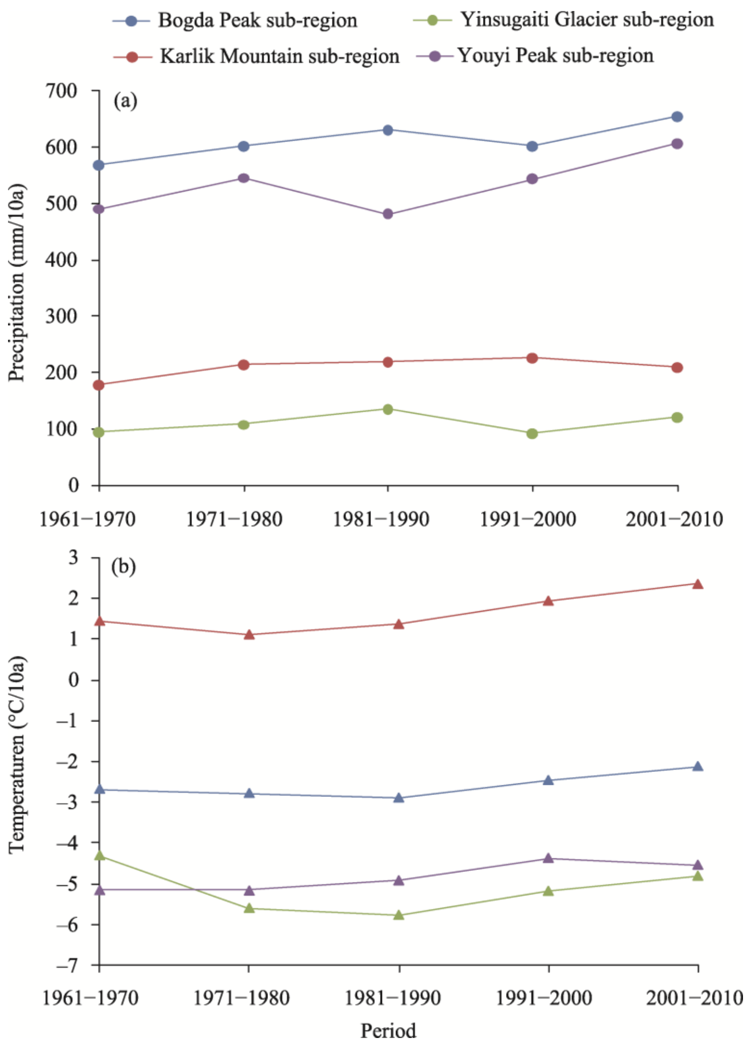

Fig. 12 Decadal change trends of precipitation (a) and temperature (b) in the 4 sub-regions during 1961–2010

4.2 Seasonal changes of precipitation and temperature

To investigate the different impacts of climate change on the glaciers in different seasons, this study divided a year into two seasons: (1) April–October being the wet season; and (2) November–March being the dry season. This division was largely based on the research on the Glacier No. 1 at the source of the Urumqi River in the Tianshan Mountains (Zhang, 2012; Liu, 2014). Annual average temperature in the Bogda Peak, Karlik Mountain, and Youyi Peak sub-regions exhibited increasing trends in the wet season ($P<0.05$; Fig. 13a and b). Annual precipitation in those sub-regions also increased in the wet season. However, it decreased insignificantly in the Youyi Peak sub-region in this season. Variation of annual precipitation in the Karlik Mountain sub-region passed the significance test ($P<0.05$), while it failed to pass the significance test in the Bogda Peak and Youyi Peak sub-regions. In the dry season (Fig. 13c and d), annual precipitation in the Bogda Peak and Youyi Peak sub-regions increased significantly and passed the significance test ($P<0.05$). However, annual precipitation in the Karlik Mountain and Yinsugaiti Glacier sub-regions remained relatively stable in the dry season with slight variations.

Accumulated temperature indicated an upward trend in the 4 sub-regions. However, it did not increase significantly in the Bogda Peak, Yinsugaiti Glacier, and Youyi Peak sub-regions, failing to pass the significance test at $P<0.05$ level. In the Karlik Mountain sub-region, accumulated temperature increased significantly throughout the dry season, passing the significance test at $P<0.05$ level. Moreover, from Table 2 we can see that there was a strong negative correlation between accumulated temperature in the wet season and glacier area in the Bogda Peak, Karlik Mountain, and Youyi Peak sub-regions, with correlation coefficient values of –0.87, –0.85, and –0.67, respectively, which all passed the significance test at $P<0.05$ level. This was consistent with the findings of Gao et al. (2000). When temperature change was greater than 0.5 ℃, the change of glacier area was mainly depended on the temperature, which was consistent with the fact that precipitation no longer plays a major role in affecting glacier area change (Gao et al., 2000).

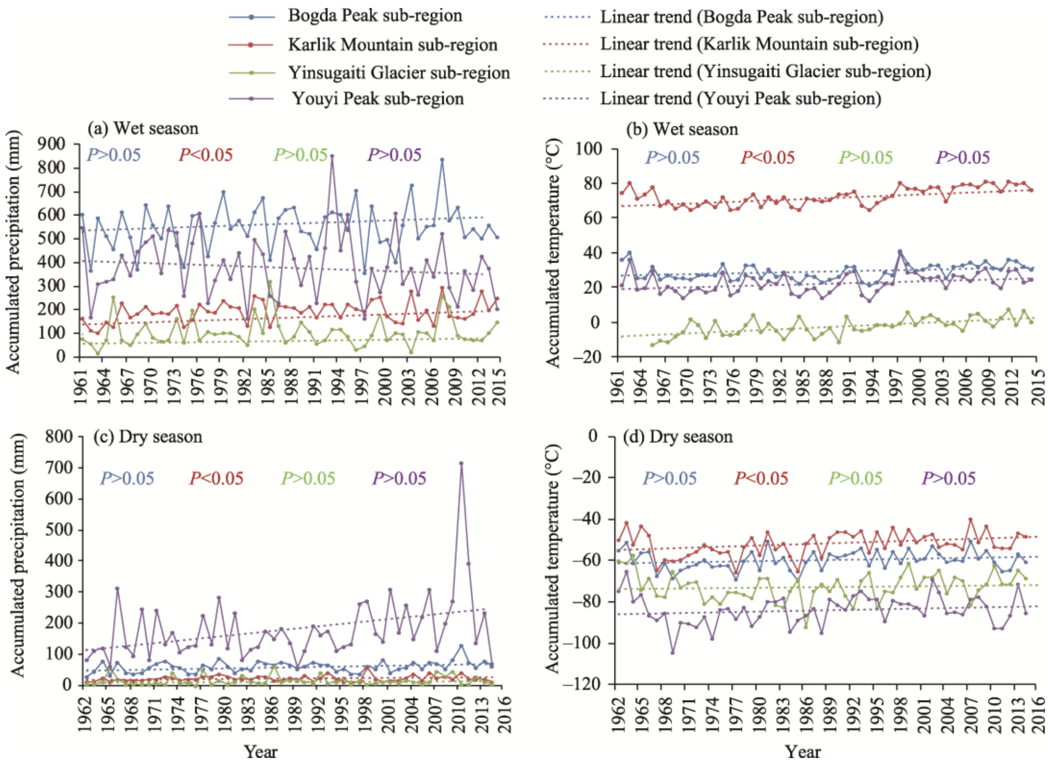

Fig. 13 Trends of key meteorological factors in the wet season (a and b) and dry season (c and d) from 1961 to 2014

Table 2 Correlations of glacier area with accumulated temperature and accumulated precipitation in the dry season and wet season in the 4 sub-regions

Sub-region	Accumulated temperature in the dry season		Accumulated precipitation in the dry season		Accumulated temperature in the wet season		Accumulated precipitation in the wet season	
	r	*P*	*r*	*P*	*r*	*P*	*r*	*P*
Bogda Peak	0.11	0.77	–0.22	0.56	–0.87	0.00	0.20	0.60
Karlik Mountain	–0.30	0.43	–0.04	0.91	–0.85	0.00	–0.09	0.82
Yinsugaiti Glacier	–0.34	0.37	0.37	0.33	–0.65	0.06	–0.28	0.47
Youyi Peak	0.59	0.09	–0.21	0.59	–0.67	0.05	0.32	0.40

Note: *r*, correlation coefficient.

To summarize, glaciers in all sub-regions showed a retreating trend in terms of slope aspect and the glacier area center of gravity, and accumulated temperature in the wet season played a major role in glacier area retreat in the Bogda Peak, Karlik Mountain, and Youyi Peak sub-regions (Li et al., 2011; Wang et al., 2013; Niu et al., 2014). However, the different glacier area retreat rates in the different sub-regions were also mainly attributed to the size and morphology of the glaciers themselves.

4.3 Response time of glacier area to changes in precipitation and temperature

The response time of glacier area change to precipitation and temperature changes in the Bogda Peak sub-region was relatively short (Fig. 14a and b). For example, when precipitation started to decrease in 1993, glacier area began to decrease around 1994, and when precipitation started to decrease in 2003, glacier area began to decrease around 2004 (Fig. 14a). Comparison of annual average temperature and glacier area showed that in the Bogda Peak sub-region, when temperature started to decrease in 1997, glacier area began to increase around 1998, and when temperature increased in 2003, glacier area started to decrease around 2004 (Fig. 14b). The results of this study supported the conclusion of Niu et al. (2014) that the Bogda Peak sub-region is dominated by small glaciers and responds faster to climate change.

A response analysis of key meteorological factors in the Karlik Mountain sub-region is presented in Figure 14c. Since about 1981, the change trend of precipitation has been rising and and then falling while glacier area change has been slowing and accelerating responsively. The relationship between glacier area and annual average temperature in the Karlik Mountain sub-region is presented in Figure 14d and the two factors demonstrated a considerable degree of consistency. The correlation coefficient value between glacier area and annual temperature was –0.72, which passed the significance test at $P<0.05$ level (Table 3).

The response analysis of climate change in the Yinsugaiti Glacier sub-region is presented in Figure 14e and f. Precipitation changes showed continuous decrease and increase trends around 1983, and glacier area changed rapidly, showing a good relationship between glacier area change and precipitation change. Around 1984, the trends of temperature change were rapid increase, increase, slow increase, and decrease, and the corresponding trends of glacier area change rate was rapid increase, increase, slow increase, and decrease, respectively. There was a good response correspondence between glacier area change and temperature change in the Youyi Peak sub-region (Fig. 14g and h). The present findings are in agreement with the research results of Yang (1987), Zhang et al. (2010), and Jiang et al. (2020)

The status of glacier area changes in Xinjiang has been investigated by many previous studies (Luo et al., 2014; Niu et al., 2014; Wang et al., 2014; Jiang et al., 2020). For example, Niu et al. (2014) concluded that glaciers in the Bogda Peak sub-region were in an accelerated retreat status, glacier shrinkage was closely related to the rapid rise in temperature in the area, and glacier ablation caused by the rise in temperature has offset the recharge of glaciers by the increase in precipitation to a certain extent. Wang (2014) showed that glacier ablation was strong in the Karlik Mountain sub-region from 1972 to 2011, and the continuous increase in glacier meltwater

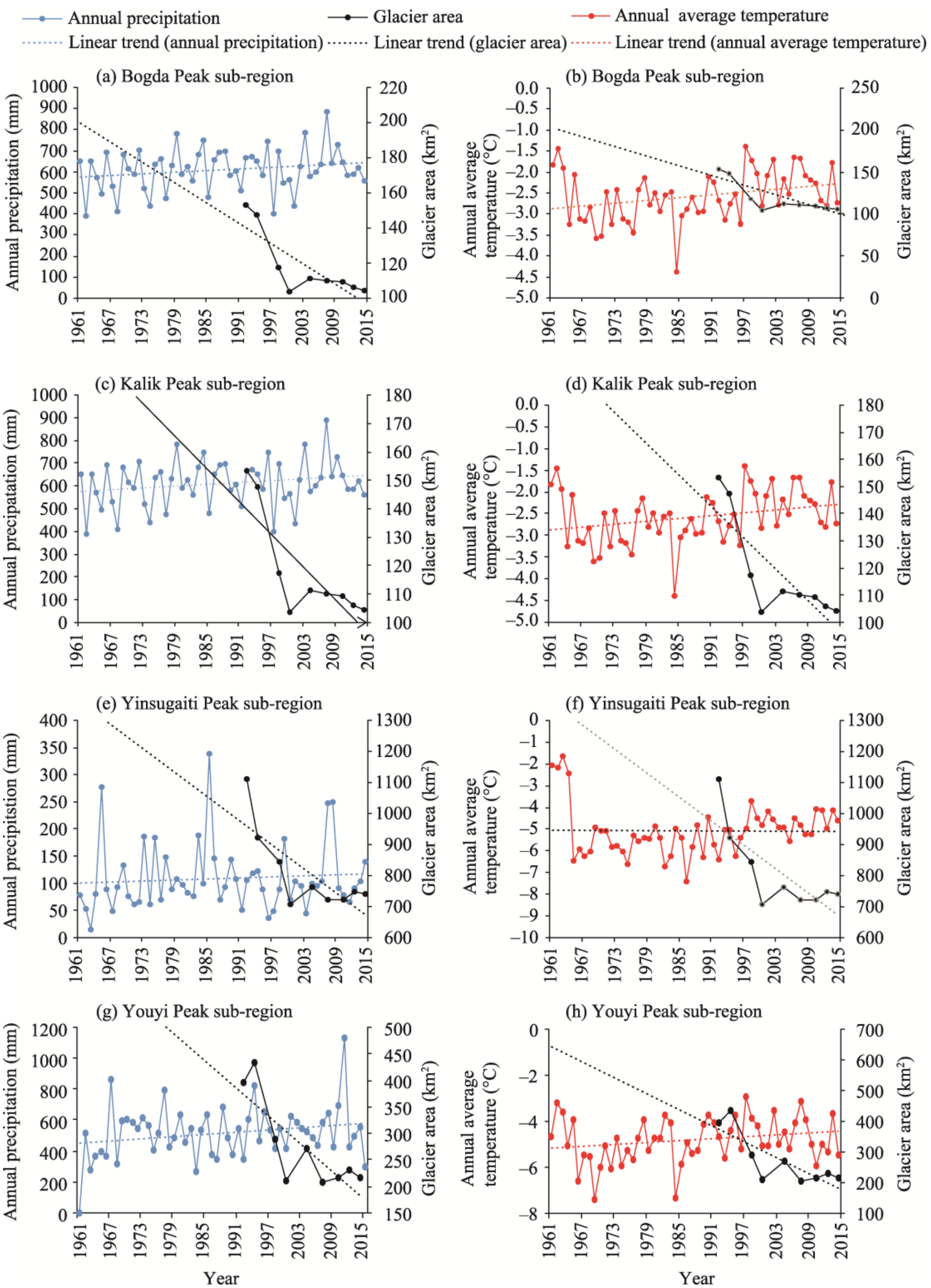

Fig. 14 Changes of glacier area along with variations of annual precipitation (a, c, e, and g) and annual average temperature (b, d, f, and h) in the 4 sub-regions from 1961 to 2014

runoff in recent years was a direct response to climate warming. Jiang et al. (2020) pointed out that the overall thickness of the Yinsugaititi Glacier was thinning from 2000 to 2014. The results of Luo et al. (2014) indicated that in the Youyi Peak sub-region, although the number of glaciers with area smaller than 1.00 km^2 accounted for 67.00% of the total glaciers, the area and reserves

were mainly concentrated in glaciers with area larger than 1.00 km^2, and the changes in thickness and reserves of several larger glaciers determined the change trend of glaciers in the region. They also suggested that small glaciers have small absolute changes and large relative change rates, and are sensitive to climate change.

Table 3 Correlations of glacier area with annual average temperature and annual precipitation in the 4 sub-regions

Sub-region	Annual precipitation		Annual average temperature	
	r	*P*	*r*	*P*
Bogda Peak	0.16	0.68	–0.20	0.60
Karlik Mountain	–0.10	0.80	–0.72	0.03
Yinsugaiti Glacier	–0.10	0.80	–0.66	0.05
Youyi Peak	–0.23	0.55	0.20	0.60

Note: *r*, correlation coefficient.

5 Conclusions

Based on Landsat TM and ETM+ images from 1990 to 2015, we compared and analyzed glacier area changes in the Bogda Peak sub-region and Karlik Mountain sub-region in the Tianshan Mountains, the Yinsugaiti Glacier sub-region in the Karakorum Mountains, and the Youyi Peak sub-region in the Altay Mountains. Glacier areas in each of the 4 sub-regions showed a general shrinking trend. However, there were different changes in glacier areas in different periods.

Glaciers in all sub-regions showed a retreating trend in terms of slope aspect and the glacier area center of gravity. From 1961 to 2014, the annual precipitation of the 4 sub-regions showed an increasing trend, while the annual average temperature of the 4 sub-regions showed a warming trend. On a seasonal time scale, glacier area changes of the Bogda Peak, Karlik Mountain, and Youyi Peak sub-regions had strong relationships with accumulated temperature in the wet season. The increase of precipitation during both the dry and wet seasons had not slowed the overall retreat of glacier areas. On an annual time scale, the correlation coefficient value between glacier area and annual average temperature was –0.72 and passed the significance test at $P<0.05$ level in the Karlik Mountain sub-region.

Compared with similar studies in this region, the time series of this study are more intensive and can capture the changes of glaciers from a more detailed perspective. Therefore, this study is important for the research of glacier changes and water resources in Xinjiang.

Acknowledgments

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